

Effect of the Niagara River Chippawa Grass Island Pool on Water Levels of Lakes Erie, St. Clair, and Michigan-Huron

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ABSTRACT. Because of renewed riparian interest stemming from the high Lake Erie water levels of the mid-1980s and mid-1990s, and the need for a concise summary of previous studies, a review and a new assessment of the impact of the Niagara River's Chippawa Grass Island Pool on Lake Erie water levels was undertaken. Numerous field and modeling studies dating from 1953 through 1988 provide different assessments of the impacts. The impacts reported by the studies range from "no measureable effect" to a 2 to 5 cm Lake Erie water level decrease. The different results are due to different methods and data, and the fact that the impacts are not directly measureable. A new Great Lakes routing model that more accurately reflects the upper Niagara River hydraulics by explicitly considering the management directive of the Chippawa Grass Island Pool is used to estimate the impacts of deviating from the present directive. The long-term impact of a 0.30 m increase or decrease from the current directive's long-term mean pool level on Lakes Erie, St. Clair, and Michigan-Huron levels is 5 cm, 4 cm, and 2 cm and -4 cm, -3 cm, and -2 cm, respectively. The lakes are minimally responsive to short-term changes in pool levels, with 50% of the Lake Erie impact achieved at about 6 months, and full impact achieved at about 2 years. The minimal lake response, the time lag to full impact, and the local problems resulting from directive deviations, make this a less favorable emergency response measure during periods of extreme lake levels than other alternatives.

INDEX WORDS: Niagara River, Lake Erie, Chippawa Grass Island Pool, water level regulation, backwater effect.

INTRODUCTION

The Niagara River is a major factor in the water balance of the Great Lakes system. It is the main outlet of water from the upper Great Lakes (Superior, Michigan, Huron, and Erie) and is the primary source of inflow to Lake Ontario. Factors affecting the upper Niagara River flow affect Lake Erie water levels and those of Lakes St. Clair and Michigan-Huron via backwater effects. The hydropower potential of the upper river has been extensively developed over the past 40 years, resulting in changes to its hydraulic regimen.

As a result of recent renewed interest on the part of Lake Erie riparians regarding the impact of hydropower operations on Lake Erie water levels, Congressional inquiries (Lee and Quinn 1994a, 1994b), and a need for a concise précis on the sub-

ject, a review of prior studies and a new assessment of hydropower impacts were undertaken. The riparian concern is that the hydropower impacts are underestimated and are responsible in part for the recent high lake levels and those of the mid-1970s and mid-1980s. This misconception stems in part from conflicting impact assessments and an inconsistent message given to the public regarding the impacts. Specifically, this study assesses the impacts of the Chippawa Grass Island Pool (CGIP) water level management on Lakes Erie, St. Clair, and Michigan-Huron water levels. The CGIP levels are primarily managed by operation of a gated control structure that partially spans the Niagara River above the Niagara Falls and Cascades. This structure was built to allow increased diversions of water for hydropower generation while meeting requirements set by the 1950 Niagara Treaty for minimum flows over Niagara Falls. Recent development of a new hydrologic response model and a new Nia-

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gara River double gauge stage-discharge relationship now make possible the assessment of long-term and short-term lake level impacts on Lake Erie, Lake St. Clair, and Lake Michigan-Huron resulting from deviations from the CGIP management directive. Impacts on the latter two lakes have not been previously reported or investigated.

This work begins with a review of past studies and field experiments investigating CGIP impacts. The current understanding of the CGIP's effects is summarized and problems inherent in quantifying the impacts are discussed. The new hydrologic response model and Lake Erie-CGIP double gauge stage-discharge relationship that represents Niagara River flows for the present hydraulic regimen are presented. Using the relationship in the hydrologic response model, the long-term and short-term impacts of deviations from the current CGIP management directive are estimated. The paper concludes by comparing and contrasting lake level impacts of the CGIP with those of the Chicago, Welland, and Long Lac-Ogoki Diversions, navigation channel improvements, Lake Superior regulation deviations, and other proposed regulation alternatives, such as increased Lake Erie outflow through use of the Black Rock Lock.

BACKGROUND

Niagara River

The Niagara River is the main outlet channel of Lake Erie and flows to Lake Ontario. It is most renowned for its spectacular falls, over which a minimum of 1,416 m³/s of water cascades more than 50 m down the face of the Niagara Escarpment. The falls divide the river into what are commonly referred to as the Upper Niagara and Lower Niagara Rivers. Because of the falls, no backwater effect is transmitted from Lake Ontario to Lake Erie (i.e., the levels of Lake Ontario do not affect those of Lake Erie). The Upper Niagara River, the subject of this study, begins with its funnel-shaped transition from Lake Erie, divides to form two channels (the western Chippawa and the eastern Tonawanda) around Grand Island, then rejoins to form the Chippawa Grass Island Pool (CGIP). At the downstream end of the CGIP, a gated control structure extends from the Canadian shore approximately half way across the width of the river toward the American shore. Below this structure, the Niagara Cascades fall about 15 m over a distance of 1.4 km to the head of the falls. Figure 1 illustrates the upper river's geography and location of the CGIP control

structure. The length of the upper river is about 36 km, with a fall of about 1.8 m over the first 6 km, and a fall of about 1.4 m over the next 30 km. Velocities range from about 3.7 m/s through the narrowest section of the river in the vicinity of the Peace Bridge to 0.6 to 0.9 m/s through the Chippawa and Tonawanda Channels and the CGIP.

Flows in the upper Niagara River are predominantly determined by Lake Erie water levels, with the downstream levels of the CGIP having a small transitory effect. Flows in the upper river averaged 5,716 m³/s for 1900–1990. The minimum monthly flow for this period is 3,940 m³/s, recorded in January, 1964, and the maximum monthly flow is 7,789 m³/s, recorded in June, 1986. However, flows in the river on an hourly and daily basis are highly variable due to Lake Erie seiche effects and winter ice transport. Daily outflows have been observed as high as 9,769 m³/s and as low as 2,441 m³/s. Storm surges, in response to wind stress on the lake surface and barometric pressure changes, and subsequent seiche activity cause water levels to vary from the lake-wide average level by as much as 2 m. During the winter (December to February) and early spring (March and April), lake ice is periodically transported to the Niagara River when strong westerly winds coincide with fragile ice cover. The ice reduces flows in the Niagara River, and occasionally causes severe ice jams with significant flow reductions. Monthly median values of ice retardation range from 100 m³/s to 225 m³/s.

Other natural factors affecting Lake Erie outflows are weed growth in the Niagara River and isostatic rebound of the Great Lakes region. Weed growth in the river from June to October reduces Lake Erie outflows by about 50 to 225 m³/s. Isostatic rebound of the earth's crust is raising the lake's outlet with respect to the lake-wide average level by about 5 cm/century.

Chippawa-Grass Island Pool Control Structure

In response to the desire to more fully utilize Lake Erie outflows for hydropower generation while preserving and enhancing the scenic spectacle of Niagara Falls, the Canadian and American governments signed a treaty concerning the uses of the waters of the Niagara River in 1950 (Department of State 1950). This treaty revised the allocation of Niagara River waters for power diversions as originally set forth by the 1909 Boundary Waters Treaty. The 1950 Niagara Treaty specifies minimum flows over the falls, with the remainder left available for

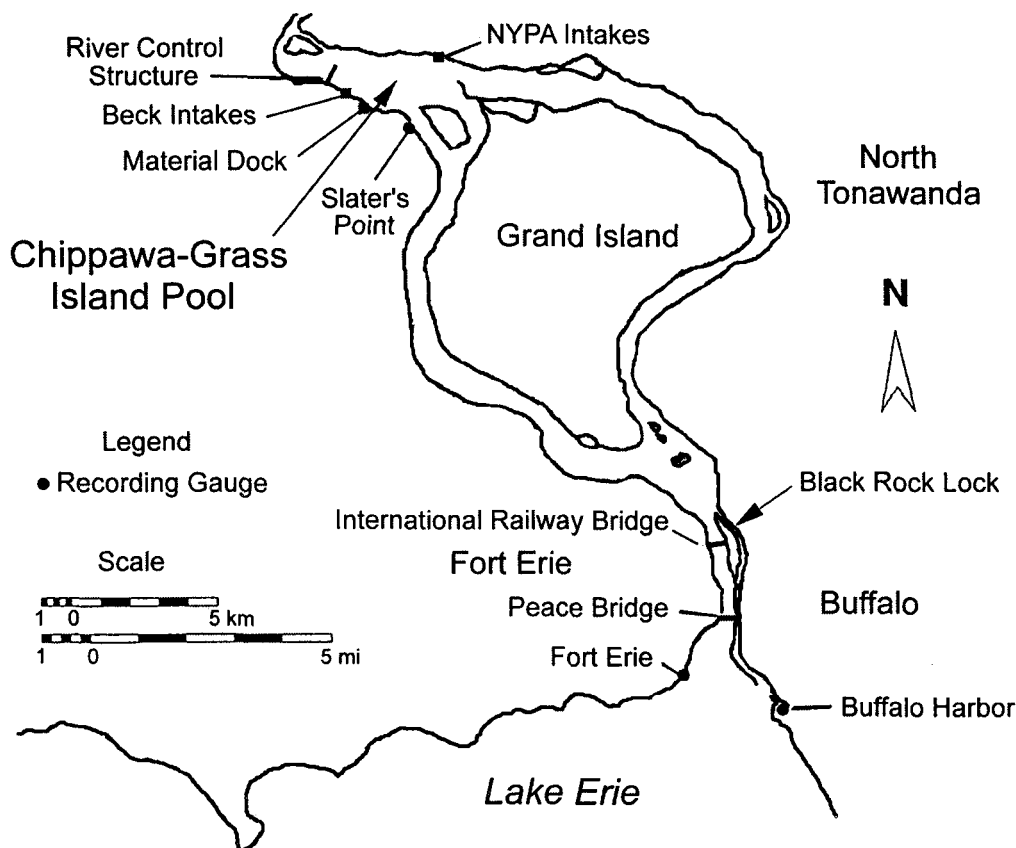


FIG. 1. Map of the Upper Niagara River (provided by the International Niagara Board of Control).

power production. From 1 April through 15 September between 8 a.m. and 10 p.m. EST, and from 16 September through 31 October between 8 a.m. and 8 p.m. EST, flows over the falls must not be less than 2,832 m³/s. At all other times, flows over the falls must not be less than 1,416 m³/s. In order to meet the requirements of the treaty, the CGIP control structure and other remedial works were constructed by the Canadian and American power authorities. Initial construction was completed in 1957, and an extension of the control structure was completed in 1963. The structure consists of eighteen 30-meter moveable gates, extending approximately 3/4 km from the Canadian shoreline, located about 1.4 km upstream of the Canadian Horseshoe Falls. The control structure, operated jointly by Ontario Hydro and the New York Power Authority, allows for increased Niagara River diversions for U.S. and Canadian hydroelectric power generation while managing the CGIP's water levels and meeting the Falls flows requirements. The International

Niagara Committee (INC), consisting of an American and a Canadian member, was established to ensure that treaty flow requirements are met. The committee reports annually to the governments (Canada's Department of Foreign Affairs and International Trade, and the U.S. State Department).

Since the increased diversions could significantly lower the CGIP levels and affect other interests, the International Joint Commission (established under the 1909 Boundary Waters Treaty) created the International Niagara Board of Control in 1953 and charged it with oversight of CGIP levels. The International Niagara Working Committee (INWC) reports to the board and provides it with technical support. Both the board and the INWC provide support to and cooperate with the INC.

Directives are issued by the board concerning the operation of the CGIP levels. The directives, in essence, ensure the maintenance of a long-term mean level of the CGIP and also establish tolerances about this level to provide latitude in facilitat-

ing control of the falls flow and diversions. The current directive, the Directive of 1993 (International Niagara Board of Control 1993), establishes the long-term mean level as 171.16 m, International Great Lakes Datum of 1985 (abbreviated as IGLD 1985), as recorded at the Material Dock gauge (Fig.1). In addition to other tolerances, the current directive also specifies that the CGIP shall not exceed 171.77 m or be less than 170.55 m. The current directive is essentially the 1973 Directive (International Niagara Board of Control 1973) with the exception of the earlier directive's use of English units and reference to the International Great Lakes Datum of 1955 (abbreviated as IGLD 1955). The 1973 Directive was substantially different from the first directive issued in 1955. The 1955 Directive (International Niagara Board of Control 1955) stipulated that the CGIP levels were to be those that would have occurred prior to the hydroelectric power expansion and construction of the remedial works for a given Niagara River flow and time of year. Operationally, this proved difficult to achieve, and the 1973 Directive was issued.

Previous Studies

Numerous studies have been conducted concerning the impact of CGIP levels on Lake Erie since treaty ratification. The studies have used various methods including field experiments, statistical analysis of recorded levels and flows, and physical and numerical models of the river.

The field experiments have involved *in situ* measurement of Niagara River flows for various CGIP levels. Different flow measurement locations and technologies were used in the studies. The technologies are documented in *Discharge Measurement Procedures on the Great Lakes Connecting Channels and the International Section of the St. Lawrence River* (Coordinating Committee on Great Lakes Basic Hydraulic and Hydrologic Data 1991) and are generally classified as conventional, moving boat, or acoustic velocity meter measurements. The flow measurements, locations, and procedures used are documented in *Hydraulic Discharge Measurements and Regimen Changes in the Great Lakes Connecting Channels and the International Section of the St. Lawrence River 1841–1993* (Coordinating Committee on Great Lakes Basic Hydraulic and Hydrologic Data 1994).

Recorded levels and flows were utilized for statistical analysis, mainly the development of water level gauge and stage-discharge relationships using

linear regression techniques. Stage-discharge relationships are equations, derived from Manning's Equation for open-channel steady flow, that relate river flows to observed upstream and downstream water levels. The physical models were actual replicas of the river and the CGIP, scaled to replicate the hydraulic characteristics of the river, and were used for assessing the increased diversions impacts and designing remediation works (primarily the CGIP control structure). The numerical models were steady-state (backwater) flow models, calibrated with field measured flows and levels. References to the statistical, physical, and numerical models are provided as appropriate in the following brief summaries of the numerous studies conducted concerning the impact of CGIP levels.

The International Niagara Falls Engineering Board, 1953

After ratification of the 1950 Niagara Treaty, the International Joint Commission established the International Niagara Falls Engineering Board and directed it to undertake the engineering investigation of remedial works necessary to meet the treaty terms (International Joint Commission 1953). The board conducted detailed hydraulic studies, including physical models of the river and the CGIP. In physical model tests conducted with increased diversions and no control structure, the board found that the CGIP level would drop as much as 1.2 m below its normal elevation and the lowering would result in lower Lake Erie levels, although the lowering was not quantified. The model tests also indicated a short-term Lake Erie outflow increase of 142 m³/s with a diversion of 4,200 m³/s from a total river flow of 6,800 m³/s. The board concluded that a control structure was necessary to preserve the regimen of the river and to ensure that Lake Erie levels and flows remained unaffected. Physical model tests with a 470 m control structure partially spanning the river indicated that CGIP levels would be from 3 to 15 cm below normal for corresponding river flows of 5,660 to 6,800 m³/s. The board agreed that the structure would initially be built to this length, and would be extended later if found necessary to maintain normal CGIP levels. A later report on the construction of the remedial works (International Joint Commission 1960) stated that for flows above 4,530 m³/s, the CGIP levels prescribed by the 1955 Directive could not be maintained. The IJC subsequently authorized the 5-gate extension of the control structure.

Water Survey of Canada, 1966

During dewatering of the American Falls for preservation and mapping efforts, Water Survey of Canada (INWC, 1972) monitored Niagara River hourly water profiles 12 and 14 November 1966, between Frenchmans Creek and Fort Erie (Fig. 1). Although the CGIP was drawn down 0.75 m, hourly profiles from a point above the Peace Bridge to Fort Erie were parallel and the observed differences were attributed to changing Lake Erie levels. Based on the analysis of the profiles, the report concluded that the effect of lowering the CGIP levels dissipated in the vicinity of the Peace Bridge.

Power Entities, 1967

In 1967, the Power Entities (INWC 1972) examined recorded CGIP levels, Lake Erie water levels recorded at Buffalo, New York, and Niagara flows to detect whether any changes in CGIP management resulted in any apparent changes in the Buffalo stage-discharge relationship. They also undertook a critical flow analysis and examined Lake Erie outflows for constant Lake Erie levels and varying CGIP levels during a weed-free month in 1965. They concluded there was no evidence that the lowering of CGIP levels had increased Lake Erie discharge.

U.S. Lake Survey, 1969

U.S. Lake Survey completed studies in 1969 of the increased diversions and CGIP management on Lake Erie levels (U.S. Lake Survey 1969) using stage-discharge relationships and a backwater model. They concluded that the flow in the Upper Niagara River is subcritical, allowing for a backwater effect of the CGIP, and estimated that Lake Erie levels had been lowered by 5 cm for average conditions.

Quinn and Smith, 1971

In 1971, Quinn and Smith (1971) conducted a hydraulic study of the upper Niagara River using a backwater model, stage-discharge relationships, and water level gauge relationships. Using the backwater model, they estimated that the effect of the increased diversions and CGIP management policy lowered Lake Erie levels by 3 cm. Using stage-discharge relationships, the effect was found to be 4 cm lowering. Using gauge relationships, they estimated a 5 cm lowering. They also concluded that the flow in the Upper Niagara River is subcritical.

International Niagara Working Committee, 1972

In 1972, the INWC (1972) reported on a detailed field experiment and numerical modeling study conducted for the board. They concluded, based on a combination of backwater model, gauge relationships, and gauge observations during CGIP draw-down, that the operation of the CGIP under the 1955 Directive produced a lowering of Lake Erie of about 3 cm. They also concluded that because of the large storage of the lake, temporary changes in the CGIP level are not reflected in the observed lake level. The INWC reported that on implementation of the increased diversions, the mean water level at the Slaters Point gauge (Fig. 1) was lowered about 9 cm with respect to the Material Dock level and that this lowering could influence the levels of Lake Erie despite maintenance of long-term mean levels as measured at Material Dock. They also concluded that use of a single gauge stage-discharge relationship resulted in errors in computed Niagara River flows.

International Niagara Working Committee, 1975

The question of whether the CGIP could be used to regulate Lake Erie levels was first considered by the International Great Lakes Levels Board. This board was formed in 1965 by the International Joint Commission at the request of the Governments of the U.S. and Canada in response to Great Lakes low water conditions. In response to the Levels Board's request in 1974, the INWC prepared and conducted a plan of study that included field measurements and numerical modeling of the river. They concluded (INWC 1975) that the outflow from Lake Erie can be temporarily increased or decreased slightly by manipulating the levels of the CGIP. Their study results indicated that for a lake level of approximately 174.83 m, a lowering of the CGIP from 171.46 m to 170.85 m results in transitory outflow increases in the range of 85 to 170 m³/s, or very roughly about 42.5 to 85 m³/s per 1/3 m lowering. They also stated that most of the benefits to Lake Erie levels from CGIP were already being achieved under the 1973 Directive because the CGIP level was maintained at a level below that which would naturally occur under high lake level conditions and above that which would naturally occur under low lake level conditions.

The INWC also gave additional reasons as to why, although technically feasible, it was not practical to regulate Lake Erie using the CGIP. Among these reasons were 1) that lowering the CGIP below

171.16 m has progressively less effect upon Lake Erie outflow, 2) the limit to which the CGIP can be lowered during the daytime hours of the tourist season, and still meet the minimum falls flow treaty requirement of 2,832 m³/s, is about 170.94 m, 3) lowering the CGIP level would reduce the flow over the American Falls and may impair the scenic spectacle, 4) during the test and during low lake levels in the past, complaints have been received about unusable water intakes and insufficient depths at docks along the upper Niagara River, and in tributaries of the Niagara River, when the CGIP level has been at elevation 170.85 m, 5) energy production at the Niagara power plants in both Canada and the United States would be impaired with significant economic losses, 6) resulting changes in outflow would affect the levels and outflows of Lake Ontario, and 7) the CGIP structure was designed and built as part of the remedial works to preserve and enhance Niagara Falls; not to regulate the level of Lake Erie.

Based on their study, the INWC concluded that at most the mean CGIP level could only be lowered less than 1/3 m below 171.16 m and that the action would have no appreciable effect upon the level of Lake Erie. The specific reduction in Lake Erie's water level, if this action were taken, was not quantified.

Coordinating Committee, 1976

In June, 1976, the Coordinating Committee on Great Lakes Basic Hydraulic and Hydrologic Data issued a publication of Lake Erie outflows from 1860 to 1964 with an addendum for 1965 to 1975 (Coordinating Committee on Great Lakes Basic Hydraulic and Hydrologic Data 1976). The publication states that the increased power diversions from the CGIP lowers the CGIP level and increases the slope of the river, and the effect of the diversions, if uncompensated, would temporarily increase the river flow by 40 m³/s per 283 m³/s of diversion resulting in an ultimate lowering of Lake Erie by 2 cm. Their analysis was based upon double gauge stage-discharge equations.

International Lake Erie Regulation Study Board, 1981

Beginning in 1977, the regulation of Lake Erie was further explored by the International Lake Erie Regulation Study Board (International Lake Erie Regulation Study Board 1981). This board was also

formed by the IJC at the request of the Governments of Canada and the U.S. This request was a result of record high water levels on Lake Erie and Lakes Michigan-Huron in the early 1970s, and as a result of the Commission's recommendations from the previous International Great Lakes Levels Board Study. The board studied three Niagara regulatory works plans in detail, but did not consider the use of the CGIP as "the regulation of the pool does not have any measurable effect on the level of Lake Erie."

Task Group 4, 1988

In response to the record high levels of 1985 and 1986, the Governments of Canada and the U.S. issued a new reference to examine and report on methods of alleviating the adverse consequences of fluctuating Great Lakes-St. Lawrence River water levels and flows. After issuing an immediate response to the Governments on a limited number of measures, the IJC created a task force to obtain additional technical information on all possible measures (International Joint Commission 1988). One of the measures focused on modified operation of the CGIP control structure. The task group charged with evaluating this measure reported that the CGIP could be operated to maintain a slightly lower mean level than that specified by the 1973 Directive. They stated that lowering the CGIP level steepens the hydraulic gradient of the river and increases the river's capacity to convey flows from Lake Erie. Based on a numerical model, and conventional and moving boat flow measurements conducted 1 to 4 June 1987, they concluded that Niagara River flows would be temporarily increased by 85 m³/s for a 1/3 m CGIP lowering, and the impact on Lake Erie would be a 4 cm lowering about 1 year after initiation of the CGIP lowering. The task force noted that extended periods of CGIP lowering would not be feasible during the winter because of the high risk of ice grounding and jams in the Niagara River. They also noted that any lowering would have adverse impacts on local riparian water intakes and marine facilities (Task Group 4 1987) and would increase treaty violations (falls flows less than treaty minimums).

International Niagara Working Committee, 1988

As a result of the studies conducted by the IJC task force, the IJC directed that additional field tests be carried out to evaluate the possible effect of the CGIP (International Niagara Working Committee 1988). These new field tests were conducted be-

tween 7 and 31 December 1987 using an acoustic velocity meter placed in the river downstream of the International Railway Bridge. During the test period, the levels of the CGIP varied above and below the 1973 Directive by 1/3 m. Statistical analysis was performed on 429 hourly measurements of water levels measured at the meter site, flows measured by the meter, Buffalo Harbor water levels, CGIP levels measured at Material Dock, and diversions by the Sir Adam Beck power plant. The INWC concluded that the analysis of the data did not identify any measurable effect on Lake Erie outflows due to changes in the CGIP level. The INWC stated that the constantly changing water levels of eastern Lake Erie (resulting in changing Niagara River flows) made it extremely difficult to measure the very small differences in river flow theoretically possible by changing CGIP levels. They also recommended that no further tests be carried out until better proven flow measurement technologies exist (Leonard 1988).

Studies Assessment

The numerous studies provide different assessments of the impacts of the CGIP on Lake Erie levels and flows. Their diverse and conflicting findings are the result of different methods and data used in their assessments. The impacts reported by these earlier studies range from "no measureable effect" to a 2 to 5 cm Lake Erie lowering. Several of the studies state that subcritical flow exists in the Upper Niagara River and that theoretically, the levels of the CGIP could have a small effect on Lake Erie levels and flows. The field studies have been unable to measure the impact on flows because the magnitude of the impact is on the same order as the flow measurement accuracy, and because it is difficult to differentiate flow changes due to CGIP management from changes due to variable Lake Erie levels. Additionally, field studies of short duration are unable to assess changes in Lake Erie levels because of the large storage capacity of the lake. Small changes in outflow will only be apparent in the lake's levels over a long period of time (a year or more). Assessment of the CGIP impacts can only be made with numerical models that explicitly consider the CGIP level as a downstream boundary condition.

HYDROLOGIC RESPONSE MODEL

We have developed a new hydrologic response model of the unregulated Great Lakes - Lakes Erie,

St. Clair, and Michigan-Huron. New model development is being conducted under the auspices of the Coordinating Committee for Great Lakes Basic Hydraulic and Hydrologic Data. The model consists of water balances and channel routing dynamics combined to estimate lake levels and connecting channel flows from water supplies to the lakes. The following equation of mass continuity, expressed for each lake in terms of quarter-monthly rates of inflow, outflow, and change in storage, is solved for the change in each lake's water level over a time interval:

$$P + R + Q_u - QR_u \pm D \pm G = E + C + Q_d - QR_d + A \left(\frac{\Delta Z}{\Delta t} \right) \quad (1)$$

Inflows are precipitation over the lake's surface (P), watershed runoff (R), diversions to the lake or its watershed (+D), groundwater contributions (+G), and inflows via the upstream connecting channel (Q_u) minus flow retardation due to ice or weed growth (QR_u). Outflows are evaporation from the lake surface (E), consumptive uses (C), diversions from the lake or its watershed (-D), groundwater losses (-G), and outflows via its downstream connecting channel (Q_d) minus flow retardation due to ice or weed growth (QR_d). The change in storage is estimated by multiplying the lake area (A) by the change in lake elevation ($\Delta Z = Z^t - Z^{t+1}$) over a time interval (Δt). The time interval is a function of the numerical stability of the solution scheme, and six timesteps per quarter-month yields satisfactory results. The connecting channel inflow and outflow rates over the time interval are approximated by

$$Q = Q^t + 1/2 \left(\frac{\delta Q^t}{\delta t} \right) \Delta t \quad (2)$$

and the connecting channel flows are computed using stage-discharge equations of the basic form (derived from Manning's flow equation):

$$Q^t = K[\phi Z_u^t + (1 - \phi)Z_d^t - ym]^a (Z_u^t - Z_d^t)^b \quad (3)$$

where Q^t is the lake outflow and Z^t is the lake level at the beginning of the time interval. The subscripts u and d denote the lakes upstream and downstream of the connecting channel, respectively. K, ϕ , a, b, and ym are constants. ϕ ranges between .5 and 1; a and b are theoretically 5/3 and 1/2, respectively; ym represents the mean bottom elevation of the connecting channel; and K is a coefficient related to channel cross-section characteristics (roughness,

hydraulic radius, and area). In practice, the values of the constants are determined by optimizing linear regressions of flows versus elevations.

Substitution of equation (3) into (2) and equation (2) into (1) for each lake, and simultaneous solution of the resulting three expressions yields the lakes' elevations at the end of the time interval. These results then serve as the initial conditions for the next time interval and the computations are repeated for the duration of the simulation period. The mean quarter-monthly and monthly elevations for a lake are found by appropriately weighting and adding the intermediate interval lake elevations. The solution also requires initial lake levels and monthly Lake Superior outflows. Depending on the coefficients used in Equation (3) for Lake Erie outflows (i.e., $\phi \neq 1$ and $b \neq 0$), downstream Niagara River water levels are also required.

This new hydrologic response model is an improvement over other existing models because Niagara River flows can be represented by double gauge stage-discharge relationships, more accurately reflecting the hydraulics of the river. Earlier models are limited to the use of single gauge relationships. Additionally, the new model is computationally efficient, modular, and independent of units and water level datums. The physical and hydraulic characteristics of the system are all inputs, resulting in a model ideal for assessments of impacts due to lake regulation, connecting channel obstruction or deepening, increased diversions and consumptive uses, and climate change.

Clites and Lee (1998) provide complete model documentation and verification. They tested the new model by replicating the Basis of Comparison (Lee 1993), prepared for the International Joint Commission's Levels Reference Study. The Basis of Comparison is a 90-year series of monthly mean Great Lakes levels and flows representing the present system's hydraulic regime, generated by the U.S. Army Corps of Engineers' Great Lakes regulation and routing model. The new model replicated the Basis of Comparison monthly mean water levels for Lakes Michigan-Huron, St. Clair, and Erie within 2 mm on average, with a maximum absolute monthly mean difference of 21 mm. Monthly mean outflows were replicated within 10 m³/s on average, with a maximum absolute monthly mean difference of 42 m³/s. These minor differences are attributed to the fact that the new model uses a different numerical solution scheme, uses the actual number of days in the month, and does not employ the extensive numerical rounding found in the Corps' model.

Clites and Lee (1998) also verified that the model conserved mass, and was numerically robust for extreme water supply scenarios (climate change scenarios, climate transposition scenarios, and the 1993 Mississippi flood). They also modelled 1974 to 1989 monthly mean lake levels and outflows using actual water supplies and diversion rates, estimated ice and weed retardation, and present system hydraulic conditions, including the 1973 CGIP Directive. They then compared the model results to the recorded monthly mean lake levels and outflows. Monthly mean water level differences averaged 19 mm, 14 mm, and 6 mm, for Lakes Michigan-Huron, St. Clair, and Erie, respectively. Correspondingly, absolute maximum differences were 61 mm, 140 mm, 192 mm. Monthly mean outflow differences averaged -7 m³/s, 1 m³/s, and 4 m³/s, for Lakes Michigan-Huron, St. Clair, and Erie, respectively. Correspondingly, absolute maximum differences were 236 m³/s, 434 m³/s, and 440 m³/s. The differences are attributed to uncertainties in the inputs (i.e., estimated water supplies to the Great Lakes and ice and weed retardation values), uncertainties in the recorded levels and flows, and the inability of any hydrologic response model to capture hydrodynamic events that occur over daily time scales but influence monthly mean values (for example, connecting channel ice jams and storm-induced seiche events).

NIAGARA RIVER STAGE-DISCHARGE RELATIONSHIP

Quinn (1998) reviews problems associated with the published Niagara River flows, corrects them, and presents new stage-discharge relationships based upon the corrected flows. His corrections eliminate discontinuities (evident from 1961 to 1981) in the historical time series coincident with changes in flow computational procedures. He concludes, based upon stage-discharge relationships, gauge relationships, and time series analysis, that the lowering of Slater's Point water levels affects Erie outflows even if the long-term mean level at Material Dock is maintained and that the 1953 Equation (a single-gauge stage-discharge relationship currently used for lake regulation analyses and water level forecasting) no longer represents the river hydraulics. His conclusions are supported by those of the 1972 INWC report.

Using recorded monthly Niagara River flows and water levels for ice-free, weed-free months from 1981 to 1987, Quinn derives a stage-discharge rela-

tionship for the present Upper Niagara River hydraulic regimen

$$Q_{\text{Niagara}} = 491.93 (0.6Z_{\text{Erie}} + 0.4Z_{\text{CGIP}} - 548.08)^{5/3} (Z_{\text{Erie}} - Z_{\text{CGIP}})^{1/2} \quad (4)$$

where

Q_{Niagara} = monthly Upper Niagara River flows,

Z_{Erie} = monthly Lake Erie water levels as recorded at Buffalo, and

Z_{CGIP} = monthly Chippawa-Grass Island Pool levels recorded at Material Dock.

The regression statistics are: rmse = 2,600 cubic feet per second (cfs); $r^2 = 0.94$. Note that this equation uses English units; flows are in cfs and levels are in feet referenced to IGLD 1955. The data were originally recorded in English units and referenced to IGLD 1955; they were not converted to metric units or the IGLD 1985 to avoid introduction of artificial errors. All computations were conducted in English units referenced to IGLD 1955, and then the final results were converted to metric. Note that Equation 4 is a form of Equation 3 with constants specific to the Niagara River ($K = 491.93$, $\phi = 0.6$, $y_m = 548.08$, $a = 5/3$, and $b = 1/2$).

MODELED EFFECTS OF THE CGIP ON LAKE ERIE LEVELS AND OUTFLOWS

Reference Simulation

A reference simulation for comparison to simulations with changes from the current CGIP management directive was made using the new hydrologic response model and stage-discharge relationship. The hydraulic conditions (connecting channel stage-discharge relationships and ice/weed retardation values) of the middle Great Lakes were represented identically as in the Basis of Comparison (Lee 1993), prepared for the International Joint Commission's Levels Reference Study, with the exception of the Niagara River stage-discharge relationship. Initial lake levels, Lake Superior outflows, and diversion rates are also those of the Basis of Comparison. Water supplies to the lakes are the recorded residually-computed monthly net basin supplies for Lakes Michigan-Huron and St. Clair, and quarter-monthly net basin supplies for Lake Erie. Consumptive use and groundwater contributions are not explicitly considered; they are implicit in the residually-computed net basin supplies. The CGIP elevation was specified in keeping with the

TABLE 1. Estimated long-term impacts of changes from the 1993 Directive (meters).

Change in CGIP Levels	Lake Michigan-Huron	Lake St. Clair	Lake Erie
from 171.16 m			
0.30	0.02	0.04	0.05
0.15	0.01	0.02	0.02
0.00	0.00	0.00	0.00
-0.15	-0.01	-0.02	-0.02
-0.30	-0.02	-0.03	-0.04

current directive as 171.16 m (equivalently 561.0 ft referenced to IGLD 1955).

Long-term Impacts from Changed Directives

To evaluate the long-term impact of modifications to the current directive, several simulations were made identical to the reference simulation with the exception of varying CGIP water levels - 0.30 m to +0.30 m from 171.16 m. The differences of their long-term annual averages from that of the reference simulation are shown in Table 1.

The long-term impact of raising the CGIP water level by 0.30 m raises the levels of Lakes Erie, St. Clair, and Michigan-Huron by 5 cm, 4 cm, and 2 cm, respectively. Lowering the CGIP water level by 0.30 m decreases their levels by 4 cm, 3 cm, and 2 cm. Decreasing the CGIP water level has less of an effect than an equal increase in the level. Note that these impacts should be interpreted as the long-term lowering given the present hydraulic conditions of the system and the water supplies of the past.

For comparison, Table 2 summarizes the long-term water level impacts of other Great Lakes system modifications. The impact of raising the CGIP water level by 0.30 m on Lake Erie water levels is less than the impacts from infilling of the Niagara River and the impacts of the Long Lac/Ogoki Diversion to Lake Superior (0.05 m vs. 0.12 m and 0.07 m). The impact of decreasing the CGIP water level by 0.30 m is equivalent to the impact of the Chicago Diversion on Lake Erie water levels (-0.04 m) but less than that of the Welland Canal (-0.12 m). The impacts of raising or lowering the CGIP water level by 0.30 m on Lake Michigan-Huron water levels (0.02 m and -0.02 m, respectively) is less than that of any of the system modifications shown in Table 2. They are one-half and one-third that of the Welland Canal and Chicago Diversion

TABLE 2. *Estimated long-term impacts of modifications to the Great Lakes system in meters (International Joint Commission 1989).*

Lake	Impacts of Channel Dredging/Infilling		Impacts of Current Diversions			Impacts of Current Regulation		Accumulated Impacts
	St. Clair/ Detroit Rivers	Niagara River	Long Lac/Ogoli	Chicago	Wellland	Superior	Ontario	
Superior	0	0	0.09	0	0	*	0	0.09
Michigan/ Huron	-0.38	0.04	0.11	-0.06	-0.04	*	0	-0.33
Erie	0	0.12	0.07	-0.04	-0.12	*	0	0.03
Ontario	0	0	0.07	-0.04	0	*	-0.09	-0.06

*Not calculated.

impacts, respectively, and are especially small in comparison to the impacts of channel dredging (-0.02 m vs. -0.38 m) and the Long Lac/Ogoki Diversion (0.02 m vs. 0.11 m). The method used here to estimate CGIP impacts is similar to that widely accepted in computing the impacts shown in Table 2.

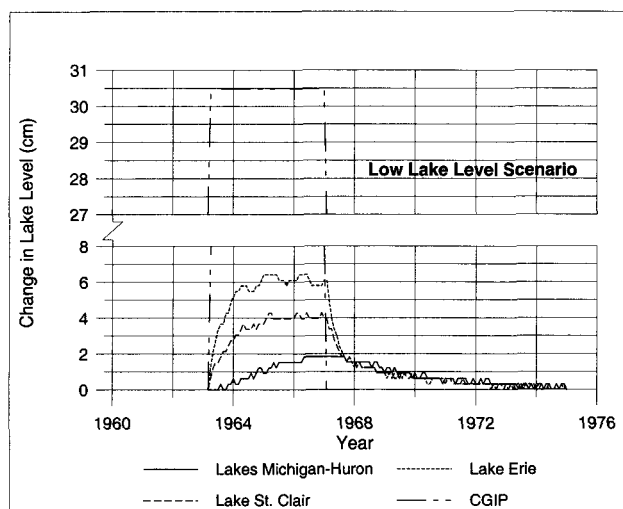
Short-term Impacts from Changed Directives

As summarized previously, manipulation of the CGIP level has been proposed in the past as a regulatory measure for ameliorating extreme high or low Lake Erie water levels. To assess the effectiveness of changing the CGIP levels on a short-term basis, a low lake level scenario (supply conditions of 1963 to 1977) and a high lake level scenario (supply conditions of 1973 to 1980) were evaluated. For each scenario, the CGIP water level was raised or lowered 0.30 m, as appropriate, when a crisis threshold water level first occurred. A crisis threshold water level signifies conditions for which effective emergency measures should be considered and implemented and beyond which major damages begin to occur (Crises Conditions Task Group 1993). The CGIP level was then returned to the current directive level when lake levels began to approach average conditions. The scenarios were extended beyond this point in time until the impacts dissipated. The differences between these scenarios and scenarios with the CGIP at the directive level are shown in Figures 2 and 3.

Figure 2 shows that for the low water supply and lake level scenario of the mid-1960s, raising the CGIP level by 0.30 m would have a maximum effect of raising Lakes Erie, St. Clair, and Michigan-Huron water levels by 6 cm, 4 cm, and 2 cm,

respectively, in addition to that already achieved by operating under the 1993 Directive. The maximum effect is achieved after 23, 24, and 39 months, correspondingly. Half of the maximum effect is achieved after 4, 7, and 20 months. Impacts of the changed CGIP levels effectively dissipate 77 months after return to the CGIP Directive level, although 50% of the impacts dissipate after 5 months, 6 months, and 24 months.

Figure 3 shows that for the high water supply and lake level scenario of the mid-1970s, lowering the CGIP level by 0.3 m would have a maximum effect of lowering Lakes Erie, St. Clair, and Michigan-Huron water levels by 2 cm, 2 cm, and 1 cm, respectively, in addition to that already achieved by

**FIG. 2.** *Low water supply and lake level scenario.*

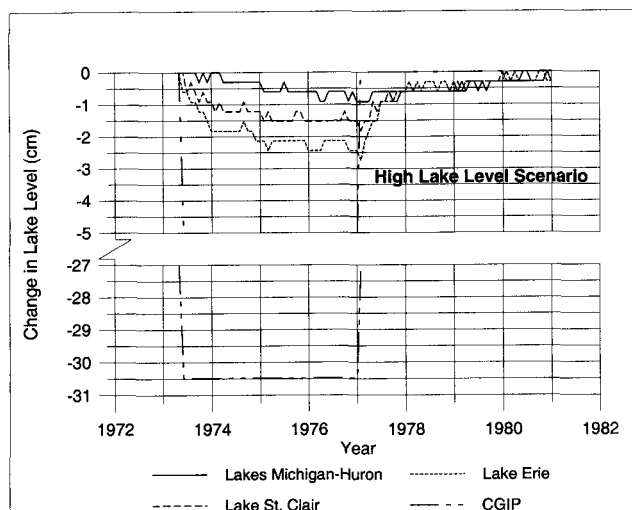


FIG. 3. High water supply and lake level scenario.

operating under the 1993 Directive. The maximum effect is achieved after 23, 24, and 36 months, correspondingly. Half of the maximum effect is achieved after 6, 6, and 12 months. Impacts of the changed CGIP levels effectively dissipate 48 months after return to the CGIP Directive level, although 50% of the impacts dissipate after 7, 9, and 27 months.

Impacts for an additional high water supply and lake level scenario of 1984 to 1989 were computed for comparison with actual measures implemented to reduce the high lake levels. In 1985, water was stored on Lake Superior and the Long Lac/Ogoki Diversion to benefit the lower lakes which were approaching previous record levels. The maximum effect of this action occurred 6 months after implementation (September, 1985) and resulted in a lowering of Lakes Erie, St. Clair, and Michigan-Huron of 3 cm, 4 cm, and 7 cm (International Lake Superior Board of Control 1985). If the CGIP levels had been reduced when Lake Erie approached its crisis level (May of 1984 for the reference simulation), the impact by September, 1985 would have been an additional lowering of Lakes Erie, St. Clair, and Michigan-Huron of 2 cm, 2 cm, and 1 cm, with maximum additional lowerings of 3 cm, 2 cm, and 1 cm achieved at the end of 1987.

Another alternative to lowering CGIP levels to increase Niagara River flows during periods of high lake levels is to increase flows through the Black Rock Lock (Fig. 1). Task Group 4 investigated this option as part of the interim studies of the 1986

Levels Reference Study (International Joint Commission 1988). They reported that flow through the existing lock culverts and butterfly valves without structural changes could increase Niagara River flows by $36 \text{ m}^3/\text{s}$, translating into a maximum Lake Erie lowering of 2 cm within 1 year. This lowering is about equivalent to that resulting from a 0.30 m CGIP lowering. However, this alternative would require curtailing navigation during periods of increased flow.

CONCLUSIONS

Previous studies have reported different and conflicting assessments of CGIP level impacts on Lake Erie levels. No Lakes St. Clair and Michigan-Huron impacts have been reported previously. The assessments have ranged from no measurable impacts to a 2 to 5 cm Lake Erie lowering. The different results are due to different methods, data, and the fact that the impacts are not directly measurable. Short-duration field studies are ineffective in measuring the impacts due to limitations in flow measurement accuracy, the dynamic nature of Lake Erie levels and Niagara River flows, and the large storage capacity of the lake. Impacts can only be assessed using numerical models with the CGIP levels as the downstream boundary condition.

The long-term impact on Lakes Erie, St. Clair, and Michigan-Huron levels of a 0.30 m increase or decrease from the current CGIP Directive long-term mean level is 5 cm, 4 cm, and 2 cm and -4 cm, -3 cm, and -2 cm, respectively. A CGIP level decrease has less lake level impact than an equivalent increase in levels. The results for Lake Erie are in keeping with findings of earlier studies that reported impacts ranging from 2 to 5 cm. Lake St. Clair and Michigan-Huron impacts are reported here for the first time. These impacts are of the same order as those of other anthropogenic changes to the Great Lakes system.

The lakes are minimally responsive to short-term changes in the CGIP levels, with 50% of the Lake Erie impact achieved at about 6 months, and full impact of lowering achieved at about 2 years. For the 1984 to 1989 supply conditions, a 0.30 m lowering of the CGIP is less effective in reducing Lake Erie, Lake St. Clair, and Lake Michigan-Huron levels than the implemented Lake Superior regulation deviations and Long Lac/Ogoki diversion reductions. Compared to increasing flows through the Black Rock Lock without structural modifications, CGIP lowering is about as effective. The feasibility

of lowering or raising CGIP levels may also restrict its use as a water level crisis response measure because of the many local problems associated with deviating from its directive level. These problems include adverse impacts on riparian water intakes and marine facilities, increased 1950 Niagara River Treaty violations, impaired American Falls spectacle, increased risk of Niagara River ice jams and associated flooding, decreased hydroelectric power production and economic losses, and adverse impacts on Lake Ontario inflows. There may also be physical limitations of the CGIP control structure that would reduce the feasibility of manipulating the CGIP levels.

A consistent message should be given to the public that manipulating the levels of the CGIP has a small impact on the water levels of Lakes Erie, St. Clair, and Michigan-Huron but that the costs and benefits of using it as a water level crisis response measure have not been quantified to date, and that it may not be operationally feasible due to local impacts and CGIP control structure limitations.

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